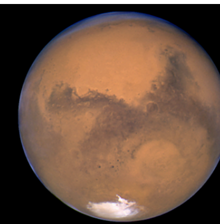
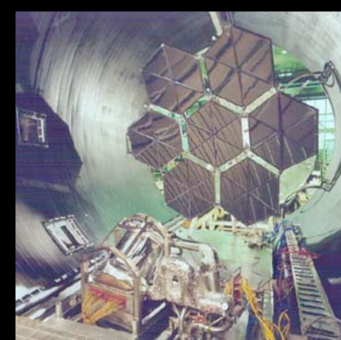
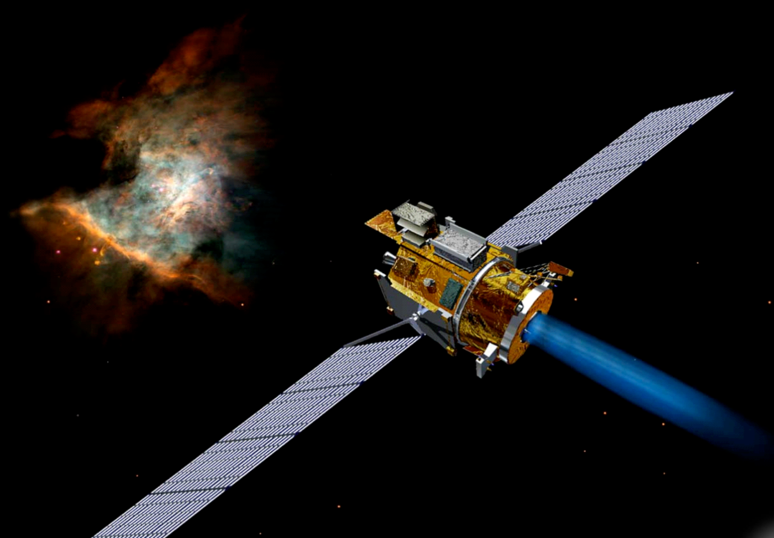
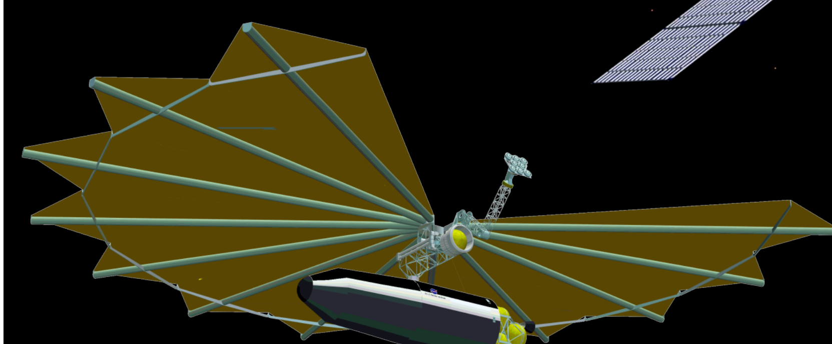


Expanding Frontiers with High Energy Power and Propulsion







NASA

Capability Road Map (CRM) 2

High Energy Power and Propulsion (HEPP)

Chair: Joseph Nainiger, NASA GRC
Co-Chair: Tom Hughes, Penn State, ARL
Deputy Chair: Jack Wheeler, DOE HDQs

Coordinators

Directorate

Betsy Park, NASA ESMD
Ray Taylor, NASA ESMD
Doug Craig, NASA ESMD

APIO

Perry Bankston NASA JPL

Team Members

NASA / JPL / DOE

Elaine Kobalka, NASA GRC
Stan Borowski, NASA GRC
Jose Davis, NASA GRC
Jeff George, NASA JSC
Rao Surampudi, NASA JPL
Sherrell Greene, DOE ORNL
Bob Wiley, DOE HDQs
George Schmidt, NASA MSFC
Wayne Bordelon, NASA MSFC

Academia

James Gilland, Ohio Aerospace Institute
Henry Brandhorst, SRI, Auburn University

Industry

Sam Bhattacharyya,
RENMAR Enterprises

Consultants

Gary Bennett, Consultant
Dave Byers, Consultant

1 General Portfolio Overview

1.1 Technology Capability Description

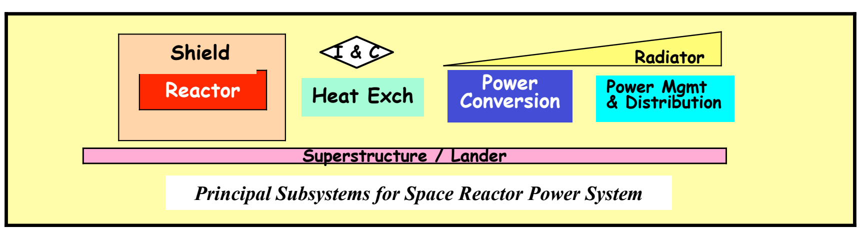
The High Energy Power and Propulsion (HEP & P) capability roadmap addresses the systems, infrastructure, and associated technologies necessary to provide power and propulsion capabilities for human and robotic exploration of space and planetary surfaces. For power, it addresses solar power, energy storage (in conjunction with solar power and as a prime source of energy), radioisotope power, and nuclear fission power. For propulsion, the roadmap addresses non-chemical propulsion systems such as electric propulsion (EP) (with solar (SEP), nuclear fission (NEP), radioisotope power (REP) as electric power providers) and nuclear thermal propulsion (NTP).

1.1.1 Solar Power

Solar power systems provide electrical power by converting solar energy into electrical energy by direct or indirect conversion. There are two types of solar power systems: Photovoltaic power systems using solar cells which convert sunlight directly into electricity, and solar thermal power systems which convert solar illumination to heat which is then used to power a thermal-to-electric power conversion subsystem. Photovoltaic power systems have been used on 99% of the space missions launched to date, and benefits include modularity, an established manufacturing base, and reasonable cost. Megawatt-class terrestrial photovoltaic and thermal power systems are operating around the world.

1.1.2 Nuclear Fission Power

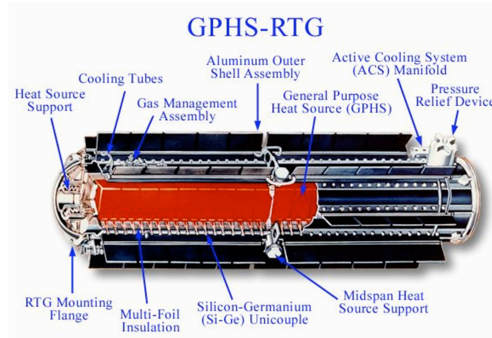
With in-space power systems, nuclear fission technology provides power independent of the proximity to the sun. For surface power, nuclear fission provides a power-rich environment for habitat and in-situ resource utilization / propellant production. Space-based fission systems differ from earth-based commercial power systems in several ways: power densities and temperatures, fuels / coolants / materials, power conversion and heat rejection technologies, shielding technologies, automated / autonomous operation and control, maintenance and refueling, and the operating environment. The U.S. has pursued numerous aerospace nuclear development programs since 1945, but the U.S. has no flight or ground test experience with space fission technology since 1972.



Principal Subsystems for Space Reactor Power System

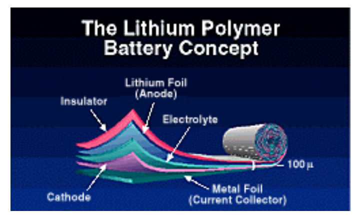
1.1.3 Radioisotope Power

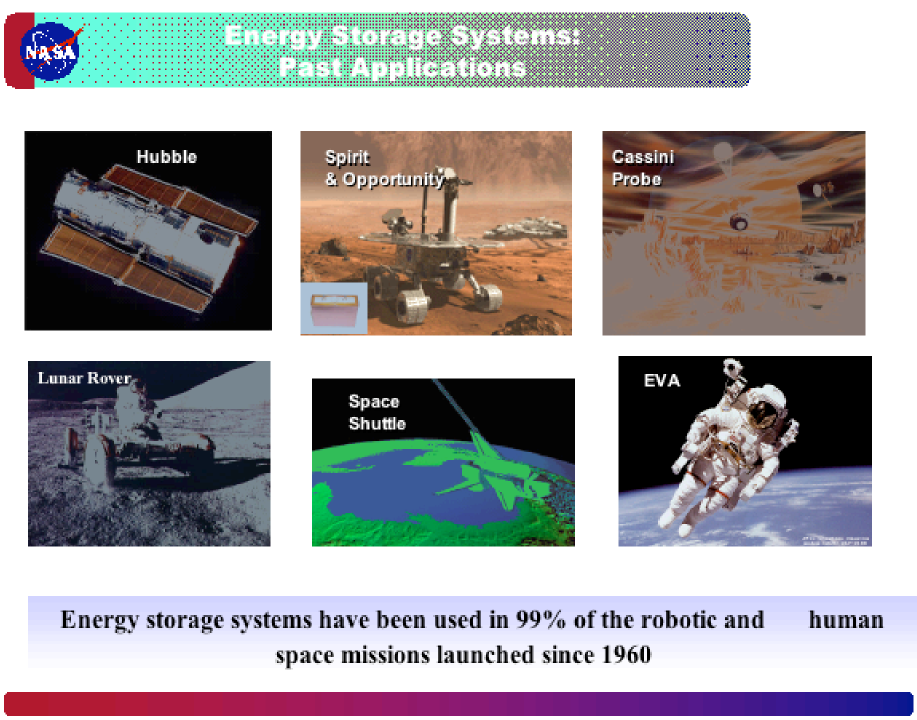
Since 1961, 40 Radioisotope Power Systems have been used on 22 US space systems. Radioisotope power systems generate electrical power by converting the heat released from the nuclear decay of radioactive isotopes (generally plutonium-238) into electricity via one of many conversion processes. Some key advantages of radioisotope power systems include their long life, compact size, and high reliability. These power systems are relatively insensitive to radiation and other environmental effects, including the distance from the Sun. The current standard radioisotope power system used in the US is the General Purpose Heat Source (GPHS) – Radioisotope Thermoelectric Generator (RTG). These units have been used with great success on the Galileo, Ulysses and Cassini missions, and nominally generate 285 watts of electrical power.



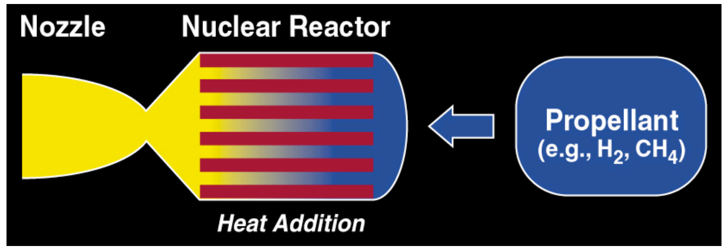
1.1.4 Energy Storage

There are two types of energy storage systems: Electrochemical energy storage and mechanical energy storage. Electrochemical energy storage systems for space applications include capacitors (high power for short durations storing very low amounts of energy), primary batteries (one-time use only, cannot be recharged), rechargeable batteries (secondary), fuel cells (primary), and regenerative fuel cells. Mechanical energy storage systems include flywheels. Future human and robotic exploration missions require advanced energy storage systems with reduced mass and volumes, longer life, and the ability to operate in extreme environments.

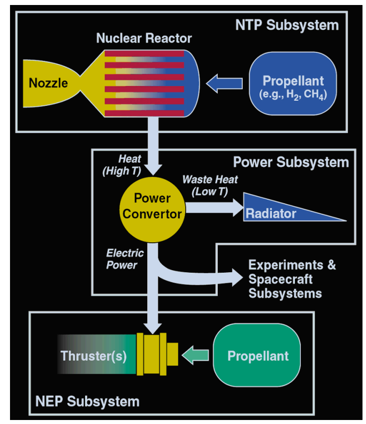




1.1.5 Nuclear Fission Propulsion

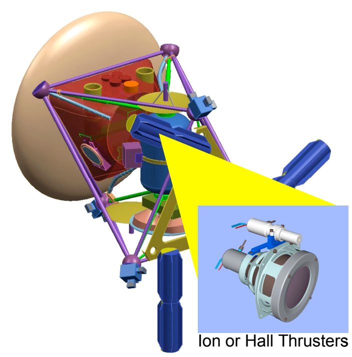


There are two basic types of Nuclear Fission Propulsion systems: Nuclear Electric Propulsion and Nuclear Thermal Propulsion. Nuclear Electric Propulsion offers a compact system capable of providing both spacecraft propulsion and electrical power for deep space robotic missions or near-Earth cargo and piloted Mars missions. The high specific impulse enables low initial propellant mass and re-supply mass. A Nuclear Thermal Propulsion system (NTP) creates thrust by heating and expanding a working fluid, such as hydrogen, in a nuclear reactor. An NTP engine has twice the efficiency of the best chemical engines due to the high energy level produced by the nuclear reactions when compared to the combustion in chemical thrusters. In the “bimodal” mode, the reactor used in an NTP vehicle is also used to continuously create electrical power for the spacecraft and crew. In a hybrid system, combining bimodal Nuclear Thermal Propulsion with Nuclear Electric Propulsion, yields rapid transit times with enhanced maneuverability.



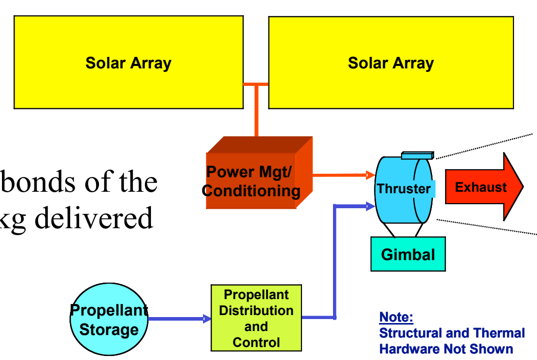
1.1.6 Radioisotope Electric Propulsion

Radioisotope electric propulsion consists of a lightweight radioisotope power system with advanced ion thrusters. Advantages of radioisotope electric propulsion include a long-life power source, not reliant on the sun, which provides propulsion power to reach the target and then provides relatively higher power levels for science payloads (since more power is needed for the ion propulsion system as opposed to past all chemical RTG spacecraft). REP also provides a propulsion system which uses much less fuel than chemical systems and therefore allows the use of smaller launch vehicles. With existing medium launchers, radioisotope electric propulsion could enable rendezvous with small planetary bodies and deep space objects. Utilizing existing heavy launchers, radioisotope electric propulsion could provide propulsive augmentation for orbital missions to the outer planets. Chemical and/or solar electric propulsion would serve as the main propulsion up to distance of Mars/asteroid belt, and the radioisotope electric propulsion system would be used for “end game” propulsion maneuvers for deceleration and orbital changes about planetary body.



1.1.7 Solar Electric Propulsion

In a solar electric propulsion system, photovoltaic arrays convert solar energy into electricity to accelerate a propellant to an exhaust velocity greater than that possible using only the chemical energy available in the molecular bonds of the propellant. For a chemical propulsion system, for every 1 kg delivered

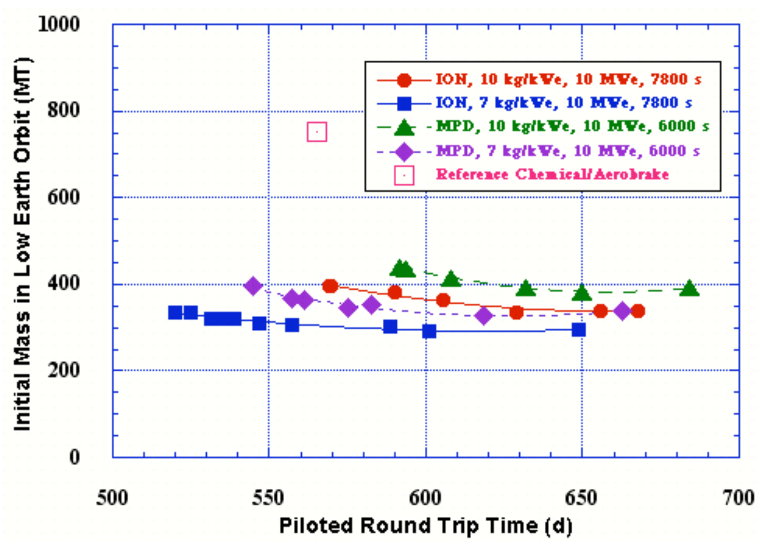


to the Lunar surface, almost 7 kg is needed in LEO. Using Solar Electric Propulsion from LEO to Lunar orbit significantly reduces this “propellant burden” and will increase delivered mass by 60-100%. Almost 200 spacecraft with on-board electric propulsion have been launched to date. Every major spacecraft producer offers electric propulsion options. The Air Force has developed and flown a single thruster operating at almost 30 kW. NASA Glenn Research Center has recently demonstrated a Hall thruster operating at 97 kW, while JPL has demonstrated operation in excess of 14,000 hours for a single xenon thruster in-space and over 30,000 hours for a single thruster in ground test.

1.2 Benefits

High energy power and propulsion systems can:

- enable extended human and robotic presence throughout the solar system through the use of advanced propulsion (SEP, NEP, REP, NTP)
- enable exploration where solar energy is limited or absent
- enable in-situ resource utilization.
- allow for “longer reach” human missions with reduced transit times
- allow for more extensive and powerful science instruments for robotic missions when they arrive at their destinations.



Nuclear Electric Propulsion provides low initial mass to earth orbit compared to conventional chemical systems.

1.3 Assumptions, qualifications, provisos, legacy activities

Based on emerging strategies, the team assumed that nuclear power and advanced propulsion systems would be required to fulfill the Vision for Space Exploration. It was also recognized that solar power and propulsion systems (especially solar electric propulsion) would be effective in many human exploration and future science applications. Sub-capabilities such as power management and distribution, power conversion, heat rejection, and materials technology were recognized as being “cross-cutting” and apply to all of the roadmap capabilities. A key assumption was each individual roadmap was intended to be technically achievable in a focused effort. No assumptions were made as to budget priorities or preferences. It was assumed that a “reasonable” program of technology development and advanced development could lead to the capabilities resulting in the roadmaps at the end of this report within the time-frame shown.

For human exploration, these included the crew exploration vehicle, lunar and Mars surface power applications, and especially piloted and cargo propulsion systems for Mars and beyond. For science missions, driving missions included lunar and Mars orbiters, planetary landers, outer planetary probes, and other demanding outer planetary missions requiring high power and/or a high degree of maneuverability and/or multiple destinations.

1.4 Key Architecture / Strategic Decisions

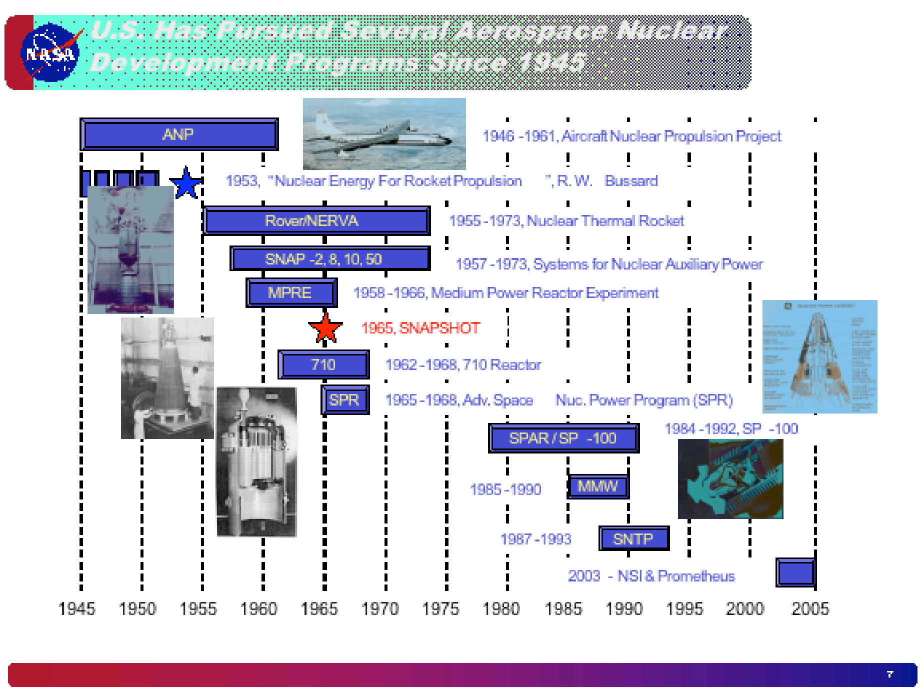
Key Architecture/Strategic Decisions	Date Decision is Needed	Impact of Decision on Capability
Decisions on crewed launch vehicle and CEV design	2006-2007	Determines CEV power and propulsion system development
Lunar Cargo Transfer Stage Decision (i.e., EDS out) and/or SEP)	2006 - 2010	Determines whether to add development of SEP cargo tug to lunar architecture. Would result in reusable SEP lunar cargo capability in 2018-2022.
Determine requirements for small probes/distributed landers (e.g., Europa lander and/or Europa sub-surface vehicle) and for Scout missions in 2013 and beyond.	2010	Initiate flight system development of milliwatt/multiwatt RPS

Key Architecture/Strategic Decisions	Date Decision is Needed	Impact of Decision on Capability
Decision on lunar cargo launch vehicle.	2010	Will determine masses, volumes, and performance capabilities for power systems and propulsion stages.
Determine power and mass requirements for Europa and Titan missions, New Frontiers 4, 5, 6, Neptune Orbiter and Europa Lander or Advanced Titan Missions.	2012	Initiate flight system hardware development of Advanced 100 We class RPS and sub-kilowatt EP for REP.
Determine NASA requirements for lunar human habitat power and Mars precursor missions (Mars Scaled Human Precursor and Mars Dynamic Mission.)	2013	Initiate multi-kilowatt RPS flight hardware development.
Decision on in-space transfer stages for human Mars missions (cargo and piloted). Initiate nuclear propulsion flight development program.	2015	Long-lead time development for Nuclear Propulsion Systems and/or MWe SEP systems .
Determine Mars surface activities for human exploration (i.e., number of crew, habitats, ISRU, etc.) Decide on and initiate flight hardware development programs.	2020	Determines Mars surface power system development, including long-lead time development for nuclear fission power.

1.5 Major Technical Challenges

2006-2010
• Nuclear fission infrastructure reestablishment (nuclear fuels, power subsystem and system ground test facilities.)
• Work in space nuclear fission power/propulsion has been dormant for many years. Need to recapture nuclear fission technology from past programs (i.e., Rover, Nerva, SP-100…) and start new developments immediately.
• Human-rated nuclear reactor shielding.
• Space Qualified Dynamic power conversion (Brayton, Stirling, or Rankine) needed for high power nuclear fission power systems. Need to develop robust, reliable dynamic power conversion.
• Heat rejection radiators for nuclear fission power systems are inherently large and current state-of-practice are massive. Need to develop lightweight, autonomously deployable heat rejection radiators.
• Development of large, long-lived electric propulsion thruster technology for nuclear and solar electric propulsion.

2006-2010 (continued)
• Development of very large (100s of kWe to MWe), high specific power (300 to 500 W/kg) solar arrays.
• Development of radiation resistant solar cells.
• As more radioisotope power and larger units are required (e.g., multi-kilowatt units) for science and exploration missions, current DOE capabilities to build Pu-238 heat sources will be insufficient. An expanded Pu-238 heat source infrastructure will be required.
• Development of high temperature nuclear fission fuels and materials for future lightweight nuclear fission power and propulsion systems.
2010 – 2020
• Qualify and flight test relatively large SEP lunar cargo stage including autonomous rendezvous, on-orbit assembly, autonomous checkout, and full operational capabilities.
• Ground test of nuclear fission power system (siting and cost issues).
2020 and Beyond
• Qualify and flight test relatively large NTP and/or MWe NEP cargo and piloted stages including autonomous rendezvous, on-orbit assembly, autonomous checkout, and full operational capabilities.



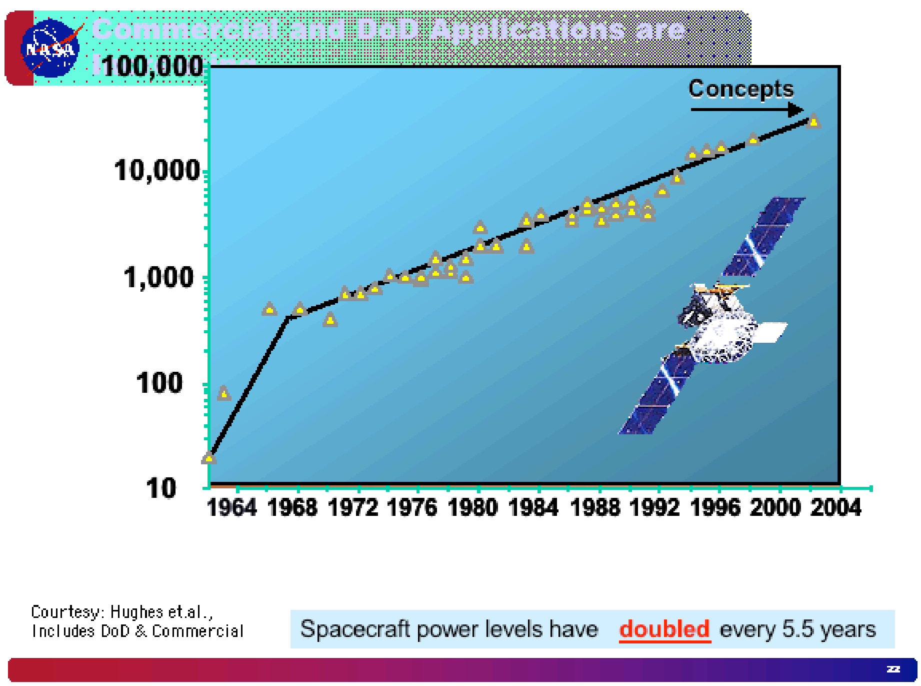
1.6 Key Capabilities and Status

The *Vision* will require extraordinary advances in power and propulsion capabilities compared to current state-of-the-practice systems. Chief among those capabilities is the development of nuclear fission power and propulsion systems and vehicles. Nuclear power and propulsion is enabling for long-term human lunar base occupancy, the use of large scale in-situ resource utilization on the lunar and Mars surfaces, and for the transport of humans and cargo to Mars. Although nuclear power and propulsion offer the promise of enabling capability, the long-lead times to develop these systems and the accompanying investment in the required reestablishment of infrastructure will provide technology and development challenges. Likewise, the development of radioisotope power systems is key to future robotic deep space probes, large robotic Mars landers and rovers, and demanding robotic missions to the surfaces of Venus, Europa, and Titan. Advances in solar power systems and capabilities will provide lighter weight and greater science capability for inner solar system robotic missions. Likewise, key developments in electric propulsion (higher performance and thruster power, and longer lived components) will enable a range of greater science capability using either solar,nuclear, or radioisotope power sources. Radioisotope electric propulsion offers significant benefits for robotic science probes to destinations having small gravity wells (i.e., Trojan asteroids).The use of reusable solar electric propulsion tugs to ferry cargo to moon and/or Mars offers a potentially cost effective means of cargo transfer.

Table 1.6 - Key Capabilities

Capability/Sub-Capability	Mission or Roadmap Enabled	Current State of Practice	Minimum Estimated Development Time (years)
Spacecraft Nuclear fission power	Robotic & human missions to Mars & beyond	Not under development	~ 10 years
Nuclear fission power for planetary surfaces	Lunar/Mars Human Missions	Under consideration	~ 13 years
Radioisotope power	Robotic & human missions of all types	Multi Mission Radioisotope Thermoelectric Generator (MMRTG) and Stirling Radioisotope Generator (SRG) under development with General Purpose Heat Source. (GPHS)	4-8 years
Solar power for spacecraft and planetary surfaces	Robotic & human missions of all types	Used on > 99% of missions to date, including spacecraft, surface and SEP.	5-8 years for multi-100 kWe arrays at 300-500 W/kg

Capability/Sub-Capability	Mission or Roadmap Enabled	Current State of Practice	Minimum Estimated Development Time (years)
Electric propulsion systems	Mars and beyond	Various ground demonstrations, limited flight experience Deep Space 1 (US) HAYABUSA (Japan) Smart 1 (ESA) ComSats (6 kW) Elite (USAF – 27 kW)	300 kWe SEP lunar cargo Tug: 12 years 1-2 MWe SEP Mars cargo Tug: 18 years REP: 5-7 years MMWe NEP: 20-25 years
Nuclear thermal propulsion	Mars Human Missions (piloted and cargo)	Extensive previous development (NERVA/Rover) in 1960s and early 1970s, but limited to studies and concept development since 1972.	15 years for Cargo Stage. 20 years for Piloted Stage



2 Detailed Portfolio Discussion

2.1 Roadmap Overview

The capability roadmap in this report is a summary level roadmap. This summary level roadmap includes only a roll up of the key sub-capabilities milestone readiness to support a particular mission requirement.

The top blue banner of the roadmap includes key missions that are pertinent to the roadmap. The green banner below represents a summary rollup of key capabilities from each of the various capability breakdown structure elements. The peach colored swim-lanes represent the individual top level capability breakdown structure element and the sub-capabilities within this roadmap. The triangles represent the date that the capability is ready to support a given mission, and the diamonds represent decision points.

Because of the large number of technologies that can be selected to produce a specific power system, and since the optimum combination of these technologies is highly dependant on the power system operating requirements, the roadmaps presented show broad system types without showing the subsystem selection process leading to the roadmapped system. Typical performance metrics are included on the system where existing data, ongoing programs or in depth study allows. The continual evolution of all the supporting technologies gives these metrics a limited life in many cases and the possibility of an unexpected, and profound, breakthrough is possible; particularly in the case of less well developed technologies. Therefore, the presented roadmaps offer a reasoned picture of how the various technologies appear to support the various missions, some of which are loosely defined themselves today. The consequence of these circumstances is that the roadmaps provide a point of departure for making coarse discriminations between alternative approaches. More detailed comparisons will be required to differentiate between the more promising approaches as mission requirements become more specific.

The team has produced both Exploration and Science roadmaps to further simplify the presentation of the extensive alternatives previously mentioned. This approach also lends itself well to the somewhat unique and different character of power systems optimized for these two classes of systems.